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AUTHOR	Mayer, Richard E.; Bayman, Piraye
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ABSTRACT

Thirty-three novices and 33 expert calculator users took a test in which they predicted what number would be in the calculator's display after a sequence of button presses (such as 2 + 3 +). Subjects' answers did not depend on the brand of calculator they actually owned. Simple production systems models were fit to the performance of each subject. Subjects differed greatly with respect to when they thought an expression would be evaluated, the order in which a chain of calculations was evaluated, and whether the display would be incremented. (Author)

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Richard E. Mayer and Piraye Bayman
University of California, Santa Barbara

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Requests for reprints should be sent to: Richard E. Mayer or Piraye Bayman. Department of Psychology, University of California, Santa Barbara, CA 93106.

Analysis of Students' Intuitions About the Operation of Electronic Calculators
RICHARD E. MAYER and PIRAYE BAYMAN, University of California, Santa Barbara

Objectives

During the past decade there has been widespread and rapid acceptance of electronic calculators in our society. Although calculators are based on a technology that did not reach mass markets until late in 1971 (Mullish, 1976), electronic calculators are becoming a common feature of our nation's classrooms. Based on a survey of articles and editorials published within the past few years in Arithmetic Teacher and Mathematics Teacher, as well as a policy statement by the National Council of Teachers of Mathematics (1976), it is clear that calculators will play an important role in the education of American students. For example, in a recent paper Bednarek & Kreisik (1976) state: "Not since the printing press has any invention had such potential for revolutionizing education, particularly mathematics education."

However, in spite of these optimistic predictions and enthusiastic endorsements, the research community has been very slow in providing information that might be useful in impending calculator-curriculum revolution. The impressive developments in improved hardware have not been matched by comparative developments in what Shneiderman (1980) calls "software psychology." This is to say, we know very little about how people come to understand calculators, what types of instruction will help people become creative users, why some people seem to never use them well, or how to design operating systems that make psychological sense. Since the calculator represents a student's first introduction to a computer, to a computer language, and to computer literacy in general, it is important to understand how humans use and understand calculators.

The objective of the present study was to determine the knowledge that ordinary users (novices) and sophisticated users (experts) have concerning the operation of hand held calculators. In particular the goal was to describe each subject's conception of the calculator's operating system, and then to make comparisons between experts and novices.

Perspectives

In order to provide a formal description of each user's knowledge, we have developed a production system (Newell & Simon, 1972) for each user. The condition for each production is a key press such as pressing a plus key (+) after pressing a digit key (e.g., 3). The action for each production is a change (or no change) in the status of the display and/or the internal registers of the calculator. There are alternative actions which may be associated with each condition; for example, if the student behaves as if a plus acts like an equals then the answer to 3 + 2 + is 5, but if the student behaves as if a plus does not act like an equals then the answer to 3 + 2 + is 2. In the former case, the display is set to the evaluated value of the expression in the register (D = eval (R)) but in the latter there is no change in the display for pressing + after 2 (D = D). The present study focused on 13 different conditions: number after +, + after number, + after +, + after =, = after number, = after +, number after x, x after number, = after x, x after =, x after x, x after +, + after x. For each condition, alternative actions were developed, so that each subject's knowledge could be represented as a list of 13 productions.

Data Source

Thirty-three novice users were recruited from the Psychology Subject Pool at the University of California, Santa Barbara. These subjects had no experience

with computers or computer programming, and were selected out of a larger sample of 46 novices because they gave consistent performance in the experiment. Thirty-three experts were recruited from Computer Science majors at the University of California, Santa Barbara. These subjects were taking an intermediate level programming course that included analyses of operating systems, and were selected out of a larger sample of 35 experts because they gave consistent performances in the experiment.

Method

A sample of 33 novice users and a sample of 33 expert users were given a four page typewritten questionnaire. The questionnaire contained 88 items such as: 2 + 3, 2 + 3 +, 2 + =, 2 + 3 + =, 2 + 3 x, 2 + +, 2 + = +, 2 + = + 3, 2 + = + = + =, 2 x + 3 =, 2 x = x = x =. For each item the subject was asked to write down the number that would be in the calculator's display after the last key was pressed (assuming the calculator was cleared at the start of the problem). The introduction made clear that the user should assume that the calculator is a typical simple one (not a HP calculator that uses reverse Polish notation).

Results and Conclusion

The data for each subject consisted of 88 numbers, i.e., the answers given.

(1) Reliability. The questionnaire consisted of two 44-item forms of the same calculator operations (such as 2 + 3 + = on one form corresponding to 7 + 3 + = on the other). The number of times a subject failed to give corresponding answers on the 44 pairs of problems was tallied (e.g., corresponding answers for the above two problems could be 3 and 3 respectively, or 5 and 10 respectively, or 10 and 20 respectively, etc.). The experts were far more consistent than the novices. However, the samples used for further analysis consist only of subjects who are highly consistent in their performance (n = 33 for each group).

(2) Comparison with user's calculator. Most of the subjects in our sample owned calculators so the answers given by each of the major models on our test was compared to the performance of each subject. For both experts and novices, Texas Instruments (TI) models produced answers which corresponded to more of our subjects' answers than any other models. This was true for subjects who owned TI calculators and equally true for subjects who owned other models or who owned none. It was also equally true for subjects who used their calculators often as compared to those who used them infrequently. Thus, the present results suggest that the operating system in simple TI models best fits the intuitions of human users. However, the answers given by the TI models failed to match the answers given by human subjects on an average of 20% of the problems for experts and 19.5% for novices. Thus, it is not sufficient to conclude that people "think like TI's operating system."

(3) Fitting a production system to the performance of each subjects. In order to provide formal descriptions of each user's conception of the operating system of a calculator, individual production systems were fit to the performance of each user. First, only the data for problems involving 6 conditions (with number, plus, and equals) was analyzed. Then, three more productions were added to each subject based on performance on problems with multiply and equals. Finally, 4 more productions were added based on the problems with conditions involving unusual sequences of plus and multiply.

As an example of how the analysis was conducted, the following table gives the typical patterns of performance on problems involving only 6 simple conditions (problems involve only number, plus, and/or equals).

Question	Group 1 Answers	Group 2 Answers	Group 3 Answers	Group 4 Answers	Group 5 Answers
2	2	2	2	2	2
2+	2	2	2	2	2
2+3	3	3	5	3	3
2+3+	5	3	5	5	5
2+3+7	7	7	12	7	7
2=	2	2	2	2	2
2+=	2	2	2	4	2
2+3=	5	5	5	5	5
2+3+=	5	5	5	10	5
2+3+7=	12	12	12	12	12
2++	2	2	2	4	4
2+=+	2	2	2	4	2
2+=+=+	2	2	2	8	2
2+=+3	3	3	5	3	3
2++=	2	2	2	8	4
2+=+=	2	2	2	8	2
2+=+=+=	2	2	2	16	2
2+-+3=	5	5	5	7	5

Group 1 corresponds to the answers given by TI models; expressions are evaluated when an = or a + key is pressed. Group 2 is identical except that expressions are evaluated only when an = key is pressed. Group 3 is identical except that expressions are evaluated when a number, a + or an = is pressed. Group 4 corresponds more closely to a Rockwell calculator and increments the display in cases where = follows +, or when + follows +. Group 5 is like Group 4 except that the display is incremented only when two pluses occur. There were 8 subjects in Group 1, 10 in Group 2, 5 in Group 3, 2 in Group 4, 1 in Group 5, and 7 miscellaneous patterns for novices; corresponding numbers for experts were 11, 7, 2, 4, 3, and 5 respectively. For example, for Group 1, + after number results in evaluating and displaying the expression but not in Group 2; or + after + results in incrementing the display for Groups 4 and 5 but not for the other groups. More detailed analysis will be presented in the full paper; major differences involve when an expression is evaluated, the order in which a chain of calculations was evaluated, and whether the display would be incremented for + being pressed after +, x after x, = after +, and = after x.

Educational and Scientific Significance

The present study is an attempt to apply the formal analysis tools of cognitive psychology to the real-world problems of classroom education. This work provides new information concerning how people understand and think about electronic calculators, and thus contributes to a growing theory of computer literacy. In addition, this work has implications for instruction since it is clear that self-taught users differ greatly in their intuitions (and hence in their effectiveness as users); this work also has practical implications for design of operating systems that are consistent with human intuitions. Finally, it is hoped that this work will serve as a stimulus for future research in helping students to get the most out of an exciting new technology. Since calculators are a student's first introduction to computers, it is important that students see that the operation of the calculator can be understood.

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